

Neutrino-nucleus quasi-elastic scattering and strange quark effects

Andrea Meucci, Carlotta Giusti, and Franco Davide Pacati

*Dipartimento di Fisica Nucleare e Teorica, Università degli Studi di Pavia and
Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, I-27100 Pavia, Italy*

A relativistic distorted-wave impulse-approximation model is applied to quasi-elastic neutrino-nucleus scattering. The bound state is obtained in the framework of the relativistic mean field theory and the final state interaction is taken into account in the scattering state. Results for the charged- and neutral-current neutrino (antineutrino) reactions on ^{12}C target nucleus are presented and the sensitivity of various quantities to the strange quark content of the nucleon weak current is discussed.

PACS numbers: 25.30.Pt; 13.15.+g; 24.10.Jv

I. INTRODUCTION

Neutrino physics has gained in recent years a wide interest that goes beyond the study of its intrinsic properties and extends to different fields, such as cosmology, astro, nuclear, and particle physics. The energy production in the sun, ν -nucleosynthesis, the dynamics of a supernova process, and possible CP-violations in neutrino oscillations are just a few examples of problems involving neutrinos in astrophysics and cosmology [1]. In hadronic and nuclear physics neutrinos can give invaluable information about the structure of the hadronic weak neutral-current and the role of the strange quark contribution to the spin structure of the nucleon. In order to investigate these fundamental questions various reactions have been proposed: deep inelastic scattering of neutrinos or of polarized charged leptons on protons [2, 3], pseudoscalar meson scattering on protons [4], and parity-violating (PV) electron scattering [5, 6, 7, 8, 9].

A number of PV electron scattering measurements have been carried out in recent years. First results from the SAMPLE experiment [10] at the MIT-Bates Laboratory and the HAPPEX collaboration [11] at Jefferson Laboratory (JLab) seemed to indicate a relatively small strangeness contribution to the proton magnetic moment [12, 13] and that the strange form factors must rapidly fall off at large Q^2 , if the strangeness radius is large [11]. The SAMPLE collaboration has recently reported [14] a new determination of the strange quark contribution to the proton magnetic form factor using a revised analysis of data in combination with the axial form factor of the proton [15]. The HAPPEX2 collaboration [16] and the G0 experiment [17] at JLab, the A4 collaboration [18] at Mainz Microtron, and the E158 experiment [19] at SLAC aim at exploring the strangeness contribution through improved measurements over a larger range of momentum transfer. First results from HAPPEX2 [20] on elastic ep scattering and on elastic scattering of polarized electrons from ^4He yield a value of the electric strange form factor of the nucleon consistent with zero while the magnetic strange form factor seems to prefer positive value though zero is still compatible with the data. Another experiment at JLab [21] plans to measure the PV asymmetry using ^{208}Pb as target nucleus. A recent review of the present situation and a discussion of the theoretical perspectives of this topic can be found in Ref. [22].

Neutrino reactions are a well-established alternative to PV electron scattering and give us complementary information about the contributions of the sea quarks to the properties of the nucleon. While PV electron scattering is essentially sensitive to the electric and magnetic strangeness of the nucleon, neutrino-induced reactions are primarily sensitive to the axial-vector form factor of the nucleon. A measurement of $\nu(\bar{\nu})$ -proton elastic scattering at Brookhaven National Laboratory (BNL) [23] suggested a non-zero value for the strange axial-vector form factor of the nucleon. However, it has been shown in Ref. [24] that the BNL data cannot provide us decisive conclusions about the strange form factors when also strange vector form factors are taken into account. The BooNE experiment [25] at Fermi National Laboratory (FermiLab) aims, through the FermiLab Intense Neutrino Scattering Scintillator Experiment (FINeSSE) [26], at performing a detailed investigation of the strangeness contribution to the proton spin Δs via neutral-current elastic scattering. A determination of the strange form factors through a combined analysis of νp , $\bar{\nu} p$, and $\bar{e} p$ elastic scattering is performed in Ref. [27].

Since an absolute cross section measurement is a very hard experimental task due to difficulties in the determination of the neutrino flux, in Ref. [28] the measurement of the ratio of proton-to-neutron cross sections in neutral-current neutrino-nucleus scattering was proposed as an alternative way to extract Δs . This ratio is sensitive to Δs but it is difficult to measure with the desired accuracy because of difficulties in the neutron detection. Thus, the FINeSSE experiment will focus on the neutral- to charged-current ratio [26]. Since a significant part of the events at FINeSSE will be from ^{12}C , nuclear structure effects have to be clearly understood in order to reach a reliable interpretation of neutrino data.

At intermediate energy, quasi-elastic electron scattering calculations [29], which were able to successfully describe a wide number of experimental data, can provide us a useful tool to study neutrino-induced processes. However, a careful analysis of neutral-current neutrino-nucleus reactions introduces additional complications, as the final neutrino cannot be measured in practice and a final hadron has to be detected: the corresponding cross sections are therefore semi-exclusive in the hadronic sector and inclusive in the leptonic one.

General review papers about neutrino-nucleus interactions can be found in Refs. [30, 31, 32, 33]. Both weak neutral-current (NC) and charged-current (CC) scattering have stimulated detailed analyses in the intermediate-energy region and different approaches have been applied to investigate such processes. The CC reaction was studied in Refs. [34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46] using a variety of methods including, for example, Fermi gas, random phase approximation (RPA) and shell model calculations. Detailed analyses of nuclear structure effects on the determination of strangeness contribution in neutral-current neutrino-nucleus scattering were performed in Refs. [40, 47], where the relativistic Fermi gas (RFG) model as well as a relativistic shell model including final state interactions (FSI) were used. The effects of FSI were also studied in Ref. [48] within the RFG model, in Ref. [28] in the framework of RPA, and in Ref. [49] in the continuum RPA (CRPA) theory. A CRPA model was developed in Ref. [50], where nucleosynthesis processes were also discussed.

The sensitivity of the neutrino-nucleus cross sections to Δs was also examined in a relativistic plane wave impulse approximation (RPWIA) in Ref. [51], where a model-independent approach based on eight structure functions was developed and applied to both NC and CC reactions. The effects of FSI are generally large on the cross section, but they are usually reduced when studying ratios of cross sections. This was discussed for the ratio of proton-to-neutron cross sections in neutral-current scattering in Refs. [40, 52, 53]. In Ref. [54] two relativistic models where FSI are treated with an optical potential and

with a multiple-scattering Glauber approximation were presented and compared. At lower energies the optical potential approach is preferable, whereas at higher energies the Glauber approximation appears more natural. Within RPWIA the two models in Ref. [54] give nearly identical results. When FSI are included the Glauber approach yields valid results down to nucleon kinetic energies of 200 MeV. The same Glauber approximation was used in Ref. [55] to discuss the sensitivity to Δ s of the helicity asymmetry of the ejected nucleon.

In this paper we present a relativistic distorted-wave impulse-approximation (RDWIA) calculation of CC and NC ν - and $\bar{\nu}$ -nucleus reactions in the quasi-elastic region, where the neutrino interacts with only one nucleon in the nucleus and the other nucleons remain spectators. The CC inclusive ν -nucleus scattering was described in Ref. [56] through a relativistic Green's function approach, that was firstly applied to the inclusive quasi-elastic electron scattering in Ref. [57] and where FSI are accounted for by means of a complex optical potential but without loss of flux. In this paper, the CC ν -nucleus reaction is considered semi-exclusive in the hadronic sector and is treated within the same RDWIA approach that was successfully applied in Refs. [58, 59, 60, 61] to electromagnetic one-nucleon knockout reactions. The NC ν -nucleus process was already studied in Ref. [62]. Here, we present a revised version of our calculations and discuss the effects of possible strange contributions to various observables.

The formalism is outlined in Sec. II. Results are presented and discussed in Sec. III. Some conclusions are drawn in Sec. IV.

II. THE FORMALISM FOR THE SEMI-EXCLUSIVE QUASI-ELASTIC SCATTERING

The $\nu(\bar{\nu})$ -nucleus cross section for the semi-exclusive process can be written as a contraction between the lepton and the hadron tensor, i.e.,

$$d\sigma = \frac{G_F^2}{2} 2\pi L^{\mu\nu} W_{\mu\nu} \frac{d^3k}{(2\pi)^3} \frac{d^3p_N}{(2\pi)^3}, \quad (1)$$

where $G_F \simeq 1.16639 \times 10^{-11} \text{ MeV}^{-2}$ is the Fermi constant, $k_i^\mu = (\varepsilon_i, \mathbf{k}_i)$, $k^\mu = (\varepsilon, \mathbf{k})$ are the four-momentum of the incident and final leptons, respectively, and \mathbf{p}_N is the momentum of the emitted nucleon. For charged-current processes G_F^2 has to be multiplied by $\cos^2 \vartheta_C \simeq 0.9749$, where ϑ_C is the Cabibbo angle.

Here, we assume the reference frame where the z -axis is parallel to the momentum transfer $\mathbf{q} = \mathbf{k}_i - \mathbf{k}$ and the y -axis is parallel to $\mathbf{k}_i \times \mathbf{k}$.

The lepton tensor is defined in a similar way as in electromagnetic knockout and can be written as in Refs. [29, 56, 62]. After projecting into the initial and the final lepton states, it separates into a symmetrical and an antisymmetrical component, i.e.,

$$L^{\mu\nu} = \frac{2}{\varepsilon_i \varepsilon} [l_S^{\mu\nu} \mp l_A^{\mu\nu}], \quad (2)$$

with

$$\begin{aligned} l_S^{\mu\nu} &= k_i^\mu k^\nu + k_i^\nu k^\mu - g^{\mu\nu} k_i \cdot k \\ l_A^{\mu\nu} &= i \epsilon^{\mu\nu\alpha\beta} k_{i\alpha} k_\beta, \end{aligned} \quad (3)$$

where $\epsilon^{\mu\nu\alpha\beta}$ is the antisymmetric tensor with $\epsilon_{0123} = -\epsilon^{0123} = 1$. The upper (lower) sign in Eq. 2 refers to $\nu(\bar{\nu})$ scattering.

The hadron tensor is given in its general form by suitable bilinear products of the transition matrix elements of the nuclear weak-current operator J^μ between the initial state $|\Psi_0\rangle$ of the nucleus, of energy E_0 , and the final states of energy E_f , that are given by the product of a discrete (or continuum) state $|n\rangle$ of the residual nucleus and a scattering state $\chi_{\mathbf{p}_N}^{(-)}$ of the emitted nucleon, with momentum \mathbf{p}_N and energy E_N . One has

$$W^{\mu\nu}(\omega, q) = \sum_n \langle n; \chi_{\mathbf{p}_N}^{(-)} | J^\mu(\mathbf{q}) | \Psi_0 \rangle \langle \Psi_0 | J^{\nu\dagger}(\mathbf{q}) | n; \chi_{\mathbf{p}_N}^{(-)} \rangle \times \delta(E_0 + \omega - E_f) , \quad (4)$$

where the sum runs over all the states of the residual nucleus. In the first order perturbation theory and using the impulse approximation, the transition amplitude is assumed to be adequately described as the sum of terms similar to those appearing in the electron scattering case [29, 58]

$$\langle n; \chi_{\mathbf{p}_N}^{(-)} | J^\mu(\mathbf{q}) | \Psi_0 \rangle = \langle \chi_{\mathbf{p}_N}^{(-)} | j^\mu(\mathbf{q}) | \varphi_n \rangle , \quad (5)$$

where $\varphi_n = \langle n | \Psi_0 \rangle$ describes the overlap between the initial nuclear state and the final state of the residual nucleus, corresponding to one hole in the ground state of the target. The single-particle current operator related to the weak current is

$$\begin{aligned} j^\mu &= F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_\nu - G_A(Q^2)\gamma^\mu\gamma^5 \quad (\text{NC}) , \\ j^\mu &= \left[F_1^V(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^V(Q^2)\sigma^{\mu\nu}q_\nu \right. \\ &\quad \left. - G_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)q^\mu\gamma^5 \right] \tau^\pm \quad (\text{CC}) , \end{aligned} \quad (6)$$

where τ^\pm are the isospin operators, κ is the anomalous part of the magnetic moment, $q^\mu = (\omega, \mathbf{q})$ with $Q^2 = |\mathbf{q}|^2 - \omega^2$ is the four-momentum transfer, and $\sigma^{\mu\nu} = (i/2)[\gamma^\mu, \gamma^\nu]$. G_A is the axial form factor and F_P is the induced pseudoscalar form factor. The weak isovector Dirac and Pauli form factors, F_1^V and F_2^V , are related to the corresponding electromagnetic form factors by the conservation of the vector current (CVC) hypothesis [30] plus, for NC reactions, a possible isoscalar strange-quark contribution F_i^s , i.e.,

$$\begin{aligned} F_i^{V,p(n)} &= \left(\frac{1}{2} - 2\sin^2\theta_W \right) F_i^{p(n)} - \frac{1}{2}F_i^{n(p)} - \frac{1}{2}F_i^s \quad (\text{NC}) , \\ F_i^V &= F_i^p - F_i^n \quad (\text{CC}) , \end{aligned} \quad (7)$$

where θ_W is the Weinberg angle ($\sin^2\theta_W \simeq 0.23143$). The electromagnetic form factors are taken from Ref. [63] and the strange form factors are taken as [32]

$$F_1^s(Q^2) = \frac{(\rho^s + \mu^s)\tau}{(1+\tau)(1+Q^2/M_V^2)^2} , \quad F_2^s(Q^2) = \frac{(\mu^s - \tau\rho^s)}{(1+\tau)(1+Q^2/M_V^2)^2} , \quad (8)$$

where $\tau = Q^2/(4M^2)$ and $M_V = 0.843$ GeV. The quantities μ_s and ρ_s are related to the strange magnetic moment and radius of the nucleus.

The axial form factor is expressed as [64]

$$\begin{aligned} G_A &= \frac{1}{2}(\tau_3 g_A - g_A^s) G \quad (\text{NC}) , \\ G_A &= g_A G \quad (\text{CC}) , \end{aligned} \quad (9)$$

where $g_A \simeq 1.26$, g_A^s describes possible strange-quark contributions, $G = (1 + Q^2/M_A^2)^{-2}$, and $\tau_3 = +1(-1)$ for proton (neutron) knockout. The axial mass has been taken from Ref. [65] as $M_A = (1.026 \pm 0.021)$ GeV, which is the weighed average of the values obtained from (quasi-)elastic neutrino and antineutrino scattering experiments. The induced pseudoscalar form factor contributes only to CC scattering and can be expressed as

$$F_P = \frac{2Mg_AG}{m_\pi^2 + Q^2} . \quad (10)$$

The differential cross section for the quasi-elastic $\nu(\bar{\nu})$ -nucleus scattering is obtained from the contraction between the lepton and hadron tensors, as in Ref. [30]. After performing an integration over the solid angle of the final nucleon, we have

$$\begin{aligned} \frac{d\sigma}{d\varepsilon d\Omega dT_N} &= \frac{G_F^2}{2\pi^2} \varepsilon^2 \cos^2 \frac{\vartheta}{2} \left[v_0 R_{00} + v_{zz} R_{zz} - v_{0z} R_{0z} + v_T R_T \right. \\ &\quad \left. \pm v_{xy} R_{xy} \right] \frac{|\mathbf{p}_N| E_N}{(2\pi)^3} . \end{aligned} \quad (11)$$

where ϑ is the lepton scattering angle and E_N the relativistic energy of the outgoing nucleon. For CC processes G_F^2 has to be multiplied by $\cos^2 \vartheta_C$. The coefficients v are given as

$$\begin{aligned} v_0 &= 1 , \quad v_{zz} = \frac{\omega^2}{|\mathbf{q}|^2} , \quad v_{0z} = \frac{\omega}{|\mathbf{q}|} , \\ v_T &= \tan^2 \frac{\vartheta}{2} + \frac{Q^2}{2|\mathbf{q}|^2} , \quad v_{xy} = \tan \frac{\vartheta}{2} \left[\tan^2 \frac{\vartheta}{2} + \frac{Q^2}{|\mathbf{q}|^2} \right]^{\frac{1}{2}} , \end{aligned} \quad (12)$$

where the mass of the final lepton has been neglected. If this is not the case, as in CC scattering, the expressions for the coefficients v can be found in Ref. [56].

The response functions R are given in terms of the components of the hadron tensor as

$$\begin{aligned} R_{00} &= \int d\Omega_N W^{00} , \quad R_{zz} = \int d\Omega_N W^{zz} , \quad R_{0z} = \int d\Omega_N 2 \operatorname{Re}(W^{0z}) , \\ R_T &= \int d\Omega_N (W^{xx} + W^{yy}) , \quad R_{xy} = \int d\Omega_N 2 \operatorname{Im}(W^{xy}) . \end{aligned} \quad (13)$$

The single differential cross section with respect to the outgoing nucleon kinetic energy T_N is obtained after performing an integration over the energy and the angle of the final lepton, i.e.,

$$\frac{d\sigma}{dT_N} = \int \left(\frac{d\sigma}{d\varepsilon d\Omega dT_N} \right) d\varepsilon d\Omega . \quad (14)$$

In the calculation of the transition amplitudes of Eq. 5 the single-particle overlap functions φ_n are taken as the Dirac-Hartree solutions of a relativistic Lagrangian, containing

scalar and vector potentials, obtained in the framework of the relativistic mean field theory [66, 67]. The relativistic single-particle scattering wave function is written as in Refs. [57, 58] in terms of its upper component, following the direct Pauli reduction scheme, i.e.,

$$\chi_{\mathbf{p}_N}^{(-)} = \left(\frac{1}{M + E + S^\dagger(E) - V^\dagger(E)} \Psi_{f+} \right), \quad (15)$$

where $S(E)$ and $V(E)$ are the scalar and vector energy-dependent components of the relativistic optical potential for a nucleon with energy E [69]. The upper component, Ψ_{f+} , is related to a two-component spinor, Φ_f , which solves a Schrödinger-like equation containing equivalent central and spin-orbit potentials, written in terms of the relativistic scalar and vector potentials [70, 71], i.e.,

$$\Psi_{f+} = \sqrt{D^\dagger(E)} \Phi_f, \quad D(E) = 1 + \frac{S(E) - V(E)}{M + E}, \quad (16)$$

where $D(E)$ is the Darwin factor.

We use in our calculations a relativistic optical potential with a real and an imaginary part which produces an absorption of flux. This is correct for an exclusive reaction, but would be incorrect for an inclusive one where the total flux must be conserved. In Refs. [56, 57, 68] we presented an approach where FSI are treated in inclusive reactions by means of a complex optical potential and the total flux is conserved. In the present investigation, we consider situations where an emitted nucleon is always detected and treat the quasi-elastic neutrino scattering as a quasi-exclusive process, where the cross section is obtained from the sum of all the integrated exclusive one-nucleon knockout channels. Some of the reaction channels which are responsible for the imaginary part of the optical potential, like fragmentation of the nucleus, re-absorption, etc., are not included in the experimental cross section when an emitted nucleon is detected. The outgoing nucleon, however, can be re-emitted after re-scattering in a detected channel, thus simulating the kinematics of a quasi-elastic reaction. The relevance of these contributions to the experimental cross section depends on kinematics and should not be too large in the situations considered in this paper. Anyhow, even if the use of an optical potential with an absorptive imaginary part can introduce some uncertainties in the comparison with data, we deem it a more correct and clearer way to evaluate the effects of FSI. We note that the same uncertainties are also present in the analysis of exclusive quasi-elastic scattering, like $(e, e'p)$, when the emission from deep states is considered. An alternative treatment can be found in Ref. [72].

III. RESULTS AND DISCUSSION

Results are presented for NC and CC neutrino and antineutrino scattering from ^{12}C in an energy range up to 1000 MeV, where the quasi-elastic one-nucleon knockout is expected to be the most important contribution to the cross section. The main aim of our investigation is to study the effects of FSI and of a non-zero contribution of the strangeness to the form factors.

In the calculations we have used the same relativistic bound state wave functions and optical potentials as in Refs. [57, 58, 59, 68], where the RDWIA was able to reproduce $(e, e'p)$, (γ, p) , and (e, e') data. The relativistic bound state wave functions have been obtained from

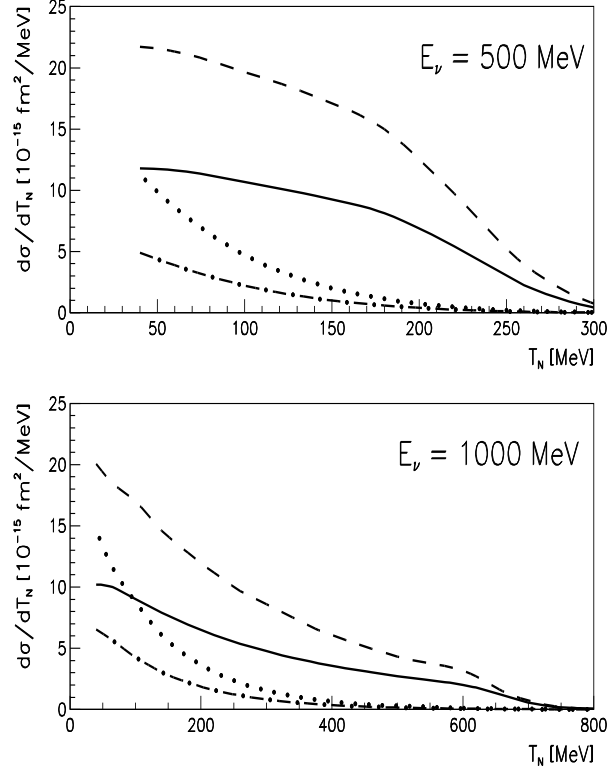


FIG. 1: Differential cross sections of the CC $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of the outgoing nucleon kinetic energy T_N . Solid and dashed lines are the results in RDWIA and RPWIA, respectively, for an incident neutrino. Dot-dashed and dotted lines are the results in RDWIA and RPWIA, respectively, for an incident antineutrino.

Ref. [66], where relativistic Hartree-Bogoliubov equations are solved in the context of a relativistic mean field theory and reproduce single-particle properties of several spherical and deformed nuclei [67]. Calculations performed with different parameterizations for the bound state wave functions give only negligible differences with respect to the results shown in this paper.

The scattering states are computed by means of the energy-dependent and A-dependent EDAD1 complex phenomenological optical potential of Ref. [69], which includes the Coulomb interaction and is fitted to proton elastic scattering data on several nuclei in an energy range up to 1040 MeV. The neutron scattering states are computed with the same optical potential but neglecting the Coulomb interaction. Calculations performed with the EDAD2 optical potential [69] do not change significantly our results.

The initial states φ_n are single-particle one-hole states in the target with an unitary spectral strength. The sum in Eq. 4 runs over all the occupied states in the shell model. In this way we include the contributions of all the nucleons in the nucleus, but disregard effects of correlations. These effects, however, are expected to be small on the semi-exclusive cross section and, moreover, should not affect the role of FSI and of the strange-quark content of the form factors, which are the aims of the present investigation.

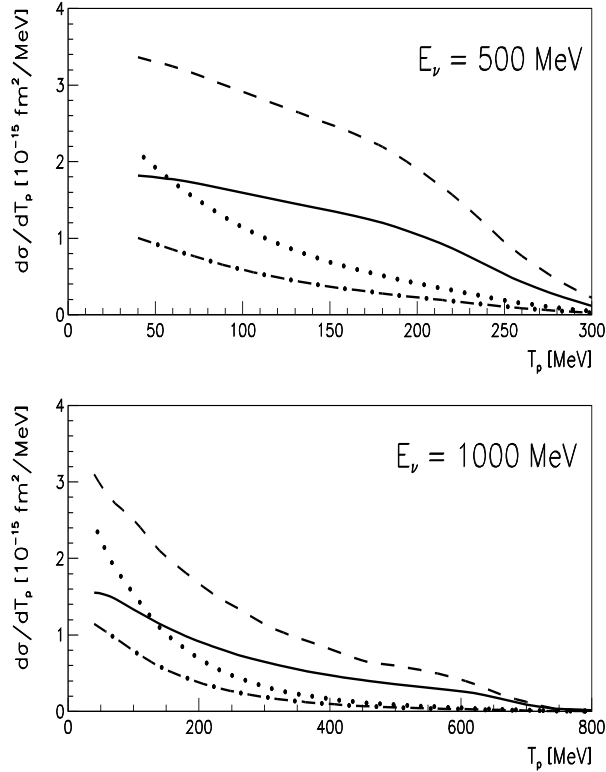


FIG. 2: Differential cross sections of the NC $\nu(\bar{\nu})$ quasi-elastic scattering on ^{12}C as a function of the outgoing proton kinetic energy T_p . Solid and dashed lines are the results in RDWIA and RPWIA, respectively, for an incident neutrino. Dot-dashed and dotted lines are the results in RDWIA and RPWIA, respectively, for an incident antineutrino. The strangeness contribution is here neglected.

In order to study the effects of FSI, we first compare results of the CC and NC $\nu(\bar{\nu})$ -nucleus cross section in RPWIA and RDWIA. In Fig. 1, the CC cross section for the $^{12}\text{C}(\nu_\mu, \mu^- p)$ and $^{12}\text{C}(\bar{\nu}_\mu, \mu^+ n)$ reactions are presented at $E_\nu = 500$ and 1000 MeV. FSI effects are large and reduce the cross section of $\simeq 50\%$. This reduction is in agreement with the results obtained in the electromagnetic one-nucleon knockout.

In Figs. 2 and 3 the NC $\nu(\bar{\nu})$ -nucleus cross sections are displayed as a function of the emitted nucleon kinetic energy for proton and neutron knockout, respectively. Also for the NC scattering the RDWIA results are reduced up to $\simeq 50\%$ with respect to the RPWIA ones. We note that the cross sections in Figs. 2 and 3 are different from our previous results of Ref. [62]. The calculations presented in this paper have been obtained after a careful check, where some inconsistencies of our previous calculations were found and eliminated. These new results are consistent with those of Ref. [54] and are larger than those of Ref. [51].

The contribution of the single-nucleon form factors to the NC and CC cross sections is investigated in Fig. 4 for proton knockout at $E_\nu = 500$ MeV. No single form factor reproduces the full cross section. In the case of CC scattering, the major contributions come from calculations with only G_A and F_1 or G_A and F_2 . These contributions are however $\simeq 30\%$ lower than the full result. This indicates that all form factors and their interference

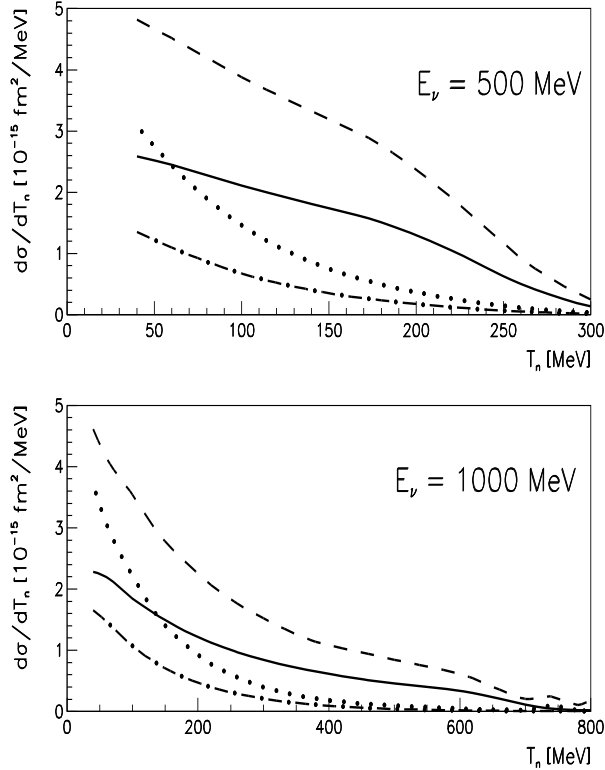


FIG. 3: The same as in Fig. 2 but for neutron knockout.

terms are important for the CC reaction. In contrast, in the NC process the weak Dirac form factor F_1 is suppressed by the mixing angle term $(1/2 - 2\sin^2\theta_W) \simeq 0.04$. The cross sections obtained with only G_A and F_2 are almost identical to the full results. The axial-vector form factor plays a dominant role in the NC reaction; in fact, when it is neglected, the cross section becomes very small.

The effects of a non-zero strange-quark contribution to the axial-vector and to the vector form factors on the NC cross sections are shown in Fig. 5 both for proton and neutron emission. A precise determination of the exact values of g_A^s , μ^s , and ρ^s is beyond the scope of this paper. Thus, here we have chosen “typical” values for the strangeness parameters to show up their effect on the results, being aware that the value of g_A^s is correlated to the value of the axial mass M_A and that the values of μ^s and ρ^s are also highly correlated (see, e.g., Ref. [52]). In our calculations we have used $g_A^s = -0.10$, $\mu^s = -0.50$, and $\rho^s = +2$. The opposite sign for μ^s and ρ^s agrees with first results from HAPPEX [11]. The results with $g_A^s = -0.10$ are enhanced in the case of proton knockout and reduced in the case of neutron knockout by $\simeq 10\%$ with respect to those with $g_A^s = 0$. The effect of μ^s is large and comparable to that of g_A^s , whereas the contribution of ρ^s is very small for neutron knockout and practically negligible for proton knockout.

The role of the strangeness contribution can also be studied in the ratio of neutrino-to-antineutrino induced NC cross sections. In Fig. 6 our RDWIA results are displayed as a function of T_N for proton and neutron knockout. This ratio is very sensitive to Δ s and

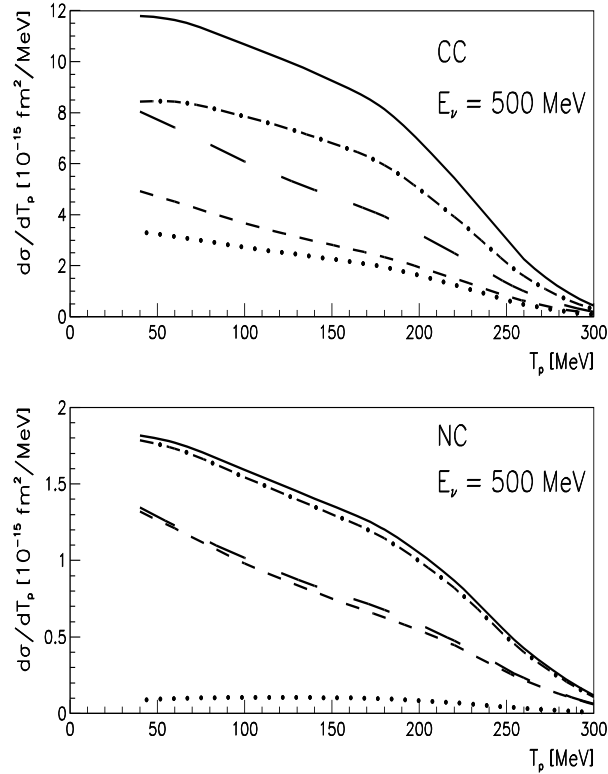


FIG. 4: Effect of the single-nucleon form factors on the CC and NC differential cross sections as a function of the outgoing proton kinetic energy. Solid lines are the full results in RDWIA, dashed lines with $G_A \neq 0$, $F_1 = F_2 = 0$, long dashed lines with $G_A \neq 0$, $F_1 \neq 0$, and $F_2 = 0$, dot-dashed lines with $G_A \neq 0$, $F_2 \neq 0$, and $F_1 = 0$, and dotted lines with $G_A = 0$, $F_1 \neq 0$, and $F_2 \neq 0$.

presents a maximum at $T_N \simeq 0.6 E_\nu$. In the case of proton knockout the ratio is reduced by g_A^s and enhanced by μ^s . In contrast, for neutron knockout the ratio is enhanced by g_A^s and reduced by μ^s . The strange radius ρ^s reduces the ratio. This effect is very small for proton knockout and larger for neutron knockout and increases with the incident neutrino and antineutrino energy.

Another interesting quantity proposed to study strangeness effects is the ratio of proton-to-neutron (p/n) NC cross sections [40, 52, 53]. This ratio is very sensitive to the strange-quark contribution as the axial-vector strangeness g_A^s interferes with the isovector contribution g_A with one sign in the numerator and with the opposite sign in the denominator (see Eq. 9). Moreover, it is expected to be less sensitive to distortion effects. The p/n ratio calculated in RDWIA for an incident neutrino or antineutrino is displayed in Fig. 7 as a function of T_N . The RPWIA results are almost coincident (up to a few percent) and are not shown in the figure. The p/n ratio for an incident neutrino is enhanced by a factor $\simeq 20 - 30\%$ when g_A^s is included and by $\simeq 50\%$ when both g_A^s and μ^s are included. A minor effect is produced also in this case by ρ^s , which gives only a slight reduction of the p/n ratio. The results for an incident antineutrino are quite different. The ratio is largely enhanced when g_A^s is included but the enhancement is canceled when also μ^s is considered.

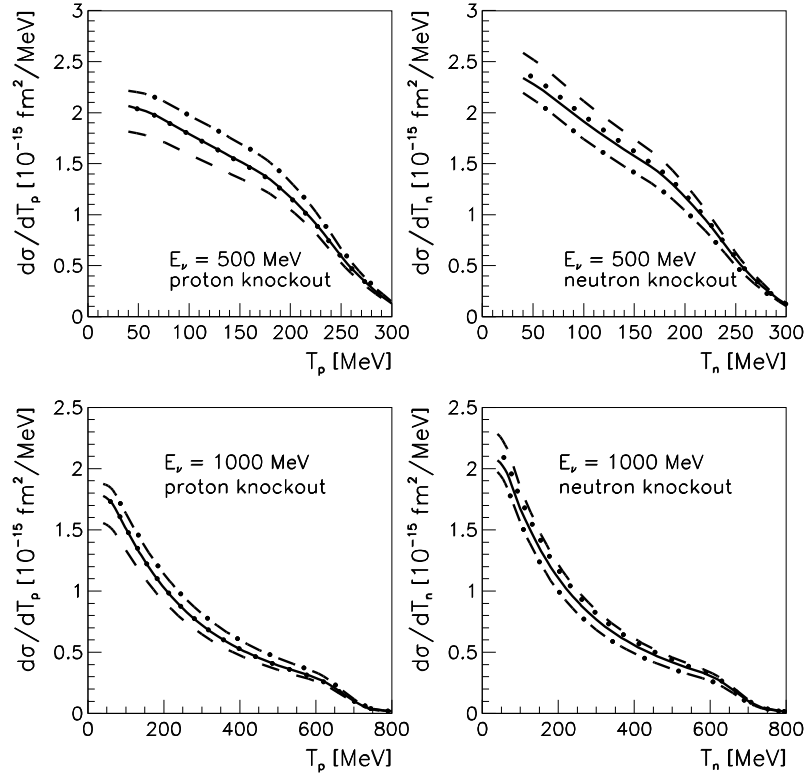


FIG. 5: Differential cross section of the NC ν quasi-elastic scattering on ^{12}C as a function of the outgoing nucleon kinetic energy. Dashed lines are the results with no strangeness contribution, solid lines with $g_A^s = -0.10$, dot-dashed lines with $g_A^s = -0.10$ and $\mu^s = -0.50$, dotted lines with $g_A^s = -0.10$ and $\rho^s = +2$.

Also in this case ρ^s plays a minor role. Precise measurements of the p/n ratio appear however problematic due to the difficulties associated with neutron detection. This is the reason why the most attractive quantity to extract experimental information about Δs seems the ratio of the neutral-to-charged (NC/CC) cross sections. In fact, although sensitive to Δs only in the numerator, the NC/CC ratio is simply related to the number of events with an outgoing proton and a missing mass with respect to the events with an outgoing proton in coincidence with a muon.

Our RDWIA results for the NC/CC ratio are presented in Fig. 8 as a function of T_N for proton and neutron emission. For the case of neutron knockout, the incident particle is supposed to be an antineutrino. The results for proton knockout show similar features at different energies of the incident neutrino. The fact that the CC cross section goes to zero more rapidly than the corresponding NC one (because of the muon mass) causes the enhancement of the ratio at large values of T_p . The inclusion of a strangeness contribution produces a somewhat constant enhancement of the results with respect to the case $\Delta s = 0$. The simultaneous inclusion of g_A^s and μ^s gives an enhancement that is about a factor of 2 larger than the one corresponding to the case with only g_A^s included. The effect of ρ^s is very small. The results for an incident antineutrino and neutron knockout appear quite different

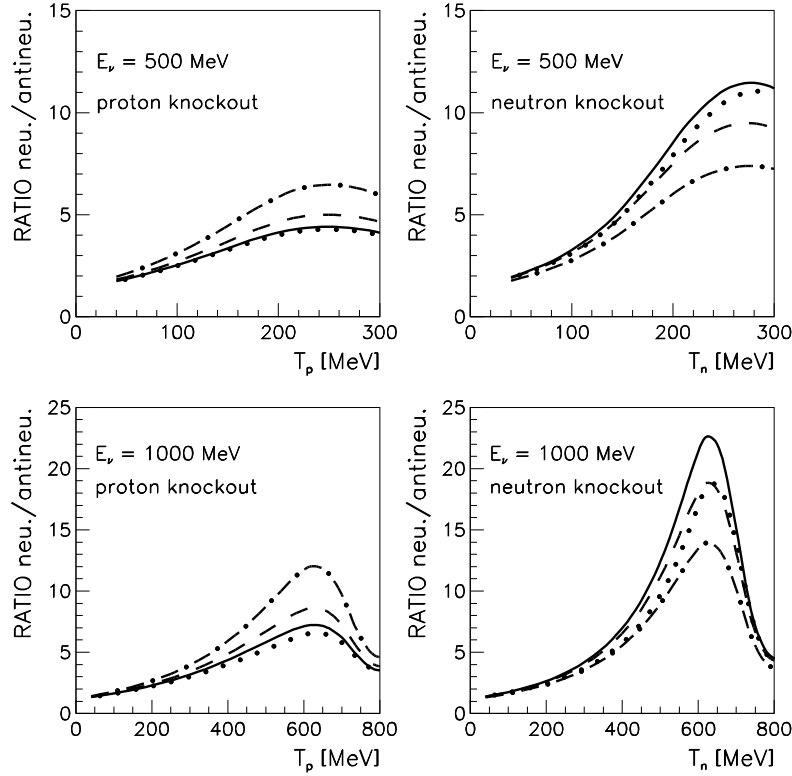


FIG. 6: Ratio of neutrino-to-antineutrino NC cross sections on ^{12}C as a function of the outgoing nucleon kinetic energy. Line convention as in Fig. 5.

at different energies of the incident antineutrino. Moreover, the effects of strangeness are somewhat energy dependent. In this case the larger effect, i.e., a reduction of the ratio, is obtained when only g_A^s is included. The global effect is reduced when also μ^s is considered.

Ratios of cross sections are attractive quantities because they are supposed to be rather insensitive to FSI between the outgoing nucleon and the residual nucleus. In order to investigate this point we show in Fig. 9 our results for the ratio of $(\text{NC}/\text{CC})_{\text{RDWIA-to-}}(\text{NC}/\text{CC})_{\text{RPWIA}}$. Results for proton knockout are always close to unity, apart from some mild oscillations, up to a few percent. In the case of an incident antineutrino and neutron knockout, the results are lower than unity. This is due both to Coulomb distortion and to the different coupling of the optical potential with proton and neutron currents, and means that FSI cannot be neglected in the determination of the NC/CC ratio with an incident antineutrino and neutron knockout. The effects of the axial-vector strangeness are also shown in Fig. 9. The results do not show significant differences with respect to the $\Delta s = 0$ case.

In order to show up the effect of the strange-quark contribution, in Ref. [40] it is proposed to study the asymmetry

$$\mathcal{A} = \frac{[(d\sigma/dT_N)_\nu - (d\sigma/dT_N)_{\bar{\nu}}]^{\text{NC}}}{[(d\sigma/dT_N)_\nu - (d\sigma/dT_N)_{\bar{\nu}}]^{\text{CC}}} . \quad (17)$$

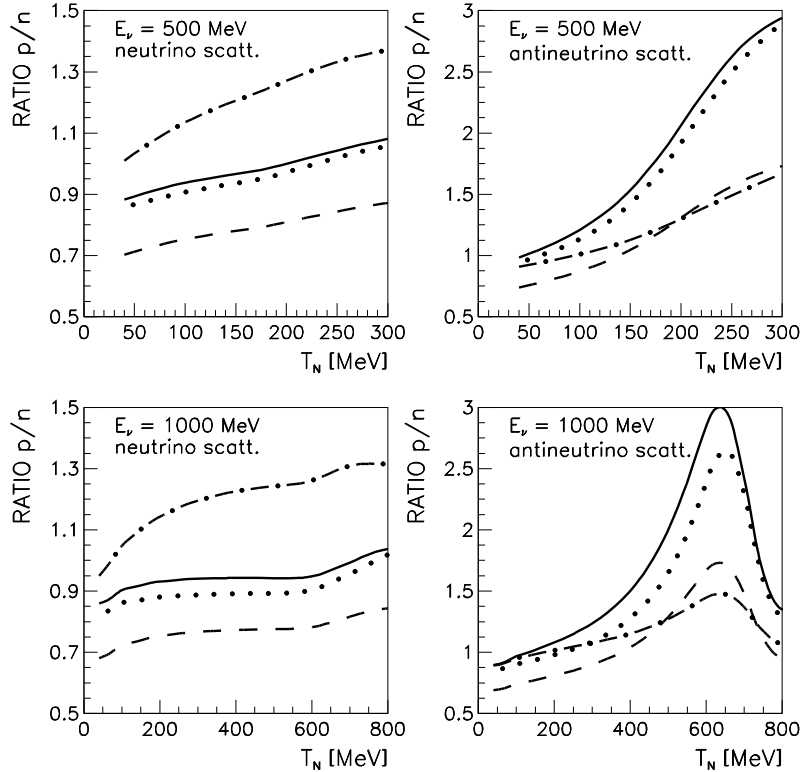


FIG. 7: Ratio of proton-to-neutron NC cross sections of the ν ($\bar{\nu}$) quasi-elastic scattering on ^{12}C as a function of T_N . Line convention as in Fig. 5.

In Fig. 10 we show our results corresponding to the emission of one proton in NC scattering as a function of T_p . The sensitivity to the strange-quark content is visible when g_A^s and μ^s are included. The role of ρ^s is also in this case less significant. These results are in agreement with those of Ref. [40].

IV. SUMMARY AND CONCLUSIONS

We have presented relativistic calculations for charged- and neutral-current $\nu(\bar{\nu})$ -nucleus quasi-elastic scattering. The reaction mechanism is assumed to be a direct one, i.e., the incident neutrino (antineutrino) interacts with only one nucleon in the target nucleus and the other nucleons behave as spectators. A sum over all single particle occupied states is performed, using an independent particle model to describe the structure of the nucleus. The scattering state is an optical-model wave function. Results for the ^{12}C target nucleus have been presented at neutrino (antineutrino) energies up to 1000 MeV.

FSI are an important ingredient of the calculations, as the optical potential produces a large reduction of the cross sections and gives a slightly different effect on proton and neutron emission. The sensitivity to the strange-quark content of the form factors has been investigated. The cross section is increased by strange-quark contribution for proton knock-

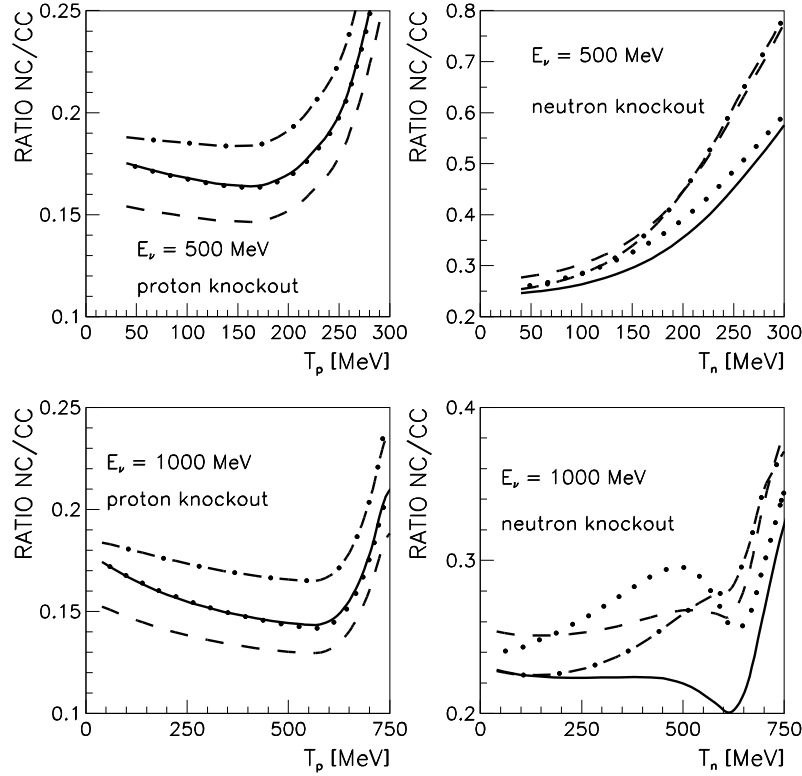


FIG. 8: Ratio of neutral-to-charged current cross sections of the ν ($\bar{\nu}$) quasi-elastic scattering on ^{12}C as a function of the outgoing nucleon kinetic energy. Line convention as in Fig. 5.

out and decreased for neutron knockout. The ratio of neutrino-to-antineutrino cross sections is very sensitive to Δs . An enhancement of the ratio of proton-to-neutron cross sections is obtained which is almost proportional to g_A^s . The enhancement is almost independent of FSI. The sensitivity to the strange-quark contribution of the vector form factors has also been discussed: μ^s enhances the p/n ratio while ρ^s gives only small effects. An attractive quantity for studying the sensitivity to strange-quark effects is the ratio of neutral-to-charged current cross sections. With $g_A^s = -0.10$ an enhancement of the NC/CC ratio of $\simeq 15\%$ relative to the case $\Delta s = 0$ is obtained. The inclusion of $\mu^s = -0.50$ produces a further increase of $\simeq 30\%$. The effects of FSI are small in the case of proton knockout but cannot be neglected in the case of neutron knockout.

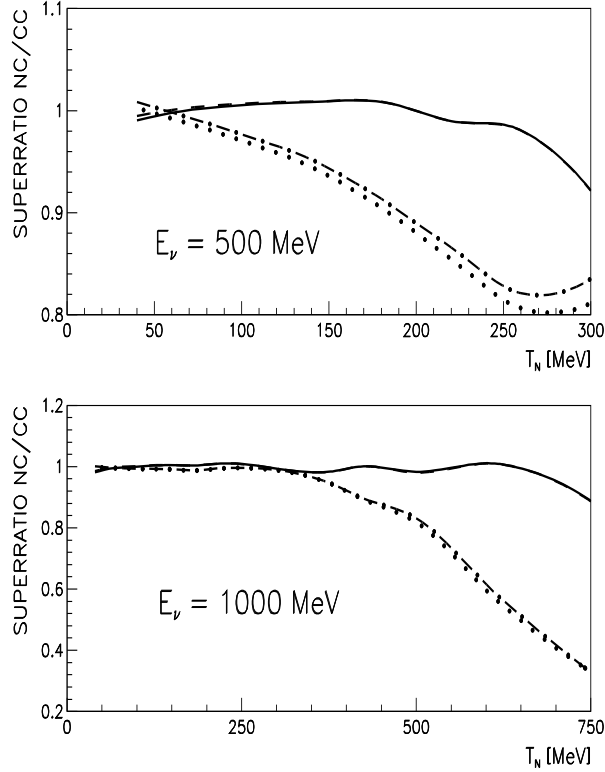


FIG. 9: Ratio of $(\text{NC/CC})_{\text{RDWIA}}$ -to- $(\text{NC/CC})_{\text{RPWIA}}$ cross sections as a function of the outgoing nucleon kinetic energy T_N . Dashed and solid lines are the results with no strangeness contribution and with $g_A^s = -0.10$, respectively, for an incident neutrino and proton knockout. Dot-dashed and dotted lines are the results with no strangeness contribution and with $g_A^s = -0.10$, respectively, for an incident antineutrino and neutron knockout.

Acknowledgments

We would like to thank Prof. Stephen Pate for useful discussions and comments.

-
- [1] J.N. Bahcall, A.M. Serenelli, and S. Basu, *Astrophys. J.* **621** (2005) L85; J.N. Bahcall, arXiv:hep-ph/0412068.
 - [2] A.O. Bazarko *et al.* [CCFR Collaboration], *Z. Phys. C* **65** (1995) 189
 - [3] D. Adams *et al.* [Spin Muon Collaboration (SMC)], *Phys. Rev. D* **56** (1997) 5330
 - [4] C.B. Dover and P.M. Fishbane, *Phys. Rev. Lett.* **64** (1990) 3115.
 - [5] G. Feinberg, *Phys. Rev. D* **12** (1975) 3575 [Erratum-ibid. *D* **13** (1976) 2164].
 - [6] J.D. Walecka, *Nucl. Phys. A* **285** (1977) 349.
 - [7] R.D. McKeown, *Phys. Lett. B* **219** (1989) 140.
 - [8] D.H. Beck, *Phys. Rev. D* **39** (1989) 3248.

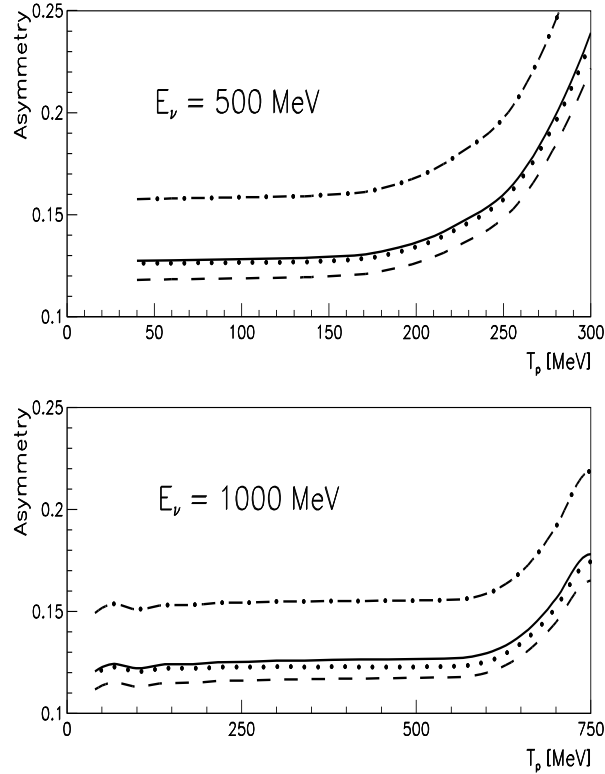


FIG. 10: The integral asymmetry of Eq. 17 for ν quasi-elastic scattering on ^{12}C as a function of the outgoing nucleon kinetic energy T_N . Line convention as in Fig. 5.

- [9] J. Napolitano, Phys. Rev. C **43** (1991) 1473.
- [10] B.A. Mueller, *et al.*, Phys. Rev. Lett. **78** (1997) 3824.
- [11] K. Aniol, *et al.*, [HAPPEX Collaboration], Phys. Rev. Lett. **82** (1999) 1096; Phys. Rev. C **69** (2004) 065501.
- [12] D.T. Spayde, *et al.*, Phys. Rev. Lett. **84** (2000) 1106.
- [13] R. Hasty, *et al.*, Science **290** (2000) 2117.
- [14] D.T. Spayde, *et al.*, Phys. Lett. B **583** (2004) 79.
- [15] T.M. Ito, *et al.*, Phys. Rev. Lett. **92** (2004) 102003.
- [16] K. Kumar and D. Lhuillier (spokespersons), JLab Experiment 99-115.
- [17] G. Batigne, Eur. Phys. J. A **19-s01** (2004) 207. Additional information can be found at <http://www.npl.uiuc.edu/epx/G0>.
- [18] D. von Harrach (spokesperson), Mainz Experiment A4; S. Baunack, Eur. Phys. J. A **18** (2003) 159. Additional information can be found at <http://www.kph.uni-mainz.de/A4/Welcome.html>.
- [19] P.L. Anthony *et al.* [SLAC E158 Collaboration], Phys. Rev. Lett. **95** (2005) 081601; Phys. Rev. Lett. **92** (2004) 181602. Additional information can be found at <http://www-project.slac.stanford.edu/e158/>
- [20] K. Aniol, *et al.*, [HAPPEX Collaboration], arXiv:nucl-ex/0506010; arXiv:nucl-ex/0506011.

- Additional information can be found at <http://hallaweb.jlab.org/parity/>
- [21] P.Soulter, R. Michaels, and G. Urcioli (spokespersons), JLab Experiment 03-011. Additional information can be found at <http://hallaweb.jlab.org/parity/prex>.
 - [22] M.J. Ramsey-Musolf, arXiv:nucl-th/0501023.
 - [23] L.A. Ahrens, *et al.*, Phys. Rev. D **35** (1987) 785.
 - [24] G.T. Garvey, W.C. Louis, and D.H. White, Phys. Rev. C **48** (1993) 761.
 - [25] E. Church, *et al.*, *A proposal for an experiment to measure $\nu_\mu \rightarrow \nu_e$ oscillation and ν_μ disappearance at FermiLab Booster: BooNE*, LA-UR-98-352, FermiLab experiment 898. More information may be found at <http://www-boone.fnal.gov/>.
 - [26] S. Brice, *et al.*, *A Proposal for a near detector experiment on the booster neutrino beamline: FINeSSE*, hep-ex/0402007. Additional information may be found at <http://home.fnal.gov/~bfleming/finese.html>.
 - [27] S.F. Pate, Phys. Rev. Lett. **92** (2004) 082002.
 - [28] G.T. Garvey, S. Krewald, E. Kolbe, and K. Langanke, Phys. Rev. C **48** (1993) 1919.
 - [29] S. Boffi, C. Giusti, F. D. Pacati, and M. Radici, *Electromagnetic Response of Atomic Nuclei*, Oxford Studies in Nuclear Physics, Vol. 20 (Clarendon Press, Oxford, 1996); S. Boffi, C. Giusti, and F. D. Pacati, Phys. Rep. **226** (1993) 1.
 - [30] J.D. Walecka, in *Muon Physics*, Vol. II, edited by V.H. Hughes and C.S. Wu (Academic Press, New York, 1975), p. 113.
 - [31] T.W. Donnelly and R.D. Peccei, Phys. Rep. **50** (1979) 1.
 - [32] W.M. Alberico, S.M. Bilenky, and C. Maieron, Phys. Rep. **358** (2002) 227.
 - [33] E. Kolbe, K. Langanke, G. Martinez-Pinedo, and P. Vogel, J. Phys. G **29** (2003) 2569.
 - [34] S.L. Mintz and M. Pourkaviani, Nucl. Phys. **A594** (1995) 346.
 - [35] J. Engel, E. Kolbe, K. Langanke, and P. Vogel, Phys. Rev. C **54** (1996) 2740.
 - [36] H. Kim, J. Piekarewicz, and C.J. Horowitz, Phys. Rev. C **51** (1995) 2739.
 - [37] S.K. Singh and F. Oset, Phys. Rev. C **48** (1993) 1246; S.K. Singh, N.C. Mukhopadhyay, and E. Oset, Phys. Rev. C **57** (1998) 2687.
 - [38] A.C. Hayes and I.S. Towner, Phys. Rev. C **61** (2000) 044603.
 - [39] C. Volpe, N. Auerbach, G. Colò, T. Suzuki, and N. Van Giai, Phys. Rev. C **62** (2000) 015501.
 - [40] W.M. Alberico, M.B. Barbaro, S.M. Bilenky, J.A. Caballero, C. Giunti, C. Maieron, E. Moya de Guerra, and J.M. Udías, Nucl. Phys. **A623** (1997) 471; Phys. Lett. **B438** (1998) 9.
 - [41] E. Kolbe, K. Langanke, F.-K. Thielemann, and P. Vogel, Phys. Rev. C **52** (1995) 3437; E. Kolbe, K. Langanke, and P. Vogel, Nucl. Phys. **A652** (1999) 91.
 - [42] N. Jachowicz, K. Heyde, J. Ryckebusch, and S. Rombouts, Phys. Rev. C **65** (2002) 025501.
 - [43] Hungchong Kim, S. Schramm, and C.J. Horowitz, Phys. Rev. C **53** (1996) 2468.
 - [44] Hungchong Kim, S. Schramm, and C.J. Horowitz, Phys. Rev. C **53** (1996) 3131.
 - [45] Y. Umino, J.M. Udias, and P.J. Mulders, Phys. Rev. Lett. **74** (1995) 4993; Phys. Rev. C **52** (1995) 3399.
 - [46] G. Co', C. Bleve, I. De Mitri, and D. Martello, Nucl. Phys. Proc. Suppl. **112** (2002) 210.
 - [47] M.B. Barbaro, A. De Pace, T.W. Donnelly, A. Molinari, M.J. Musolf, Phys. Rev. C **54** (1996) 1954.
 - [48] C. Bleve, G. Co', I. De Mitri, P. Bernardini, G. Mancarella, D. Martello, and A. Surdo, Astropart. Phys. **16** (2001) 145;
 - [49] A. Botrugno and G. Co', Nucl. Phys. **A761** (2005) 200.
 - [50] N. Jachowicz, S. Rombouts, K. Heyde, and J. Ryckebusch, Phys. Rev. C **59** (1999) 3246.
 - [51] B.I.S. van der Ventel, and J. Piekarewicz, Phys. Rev. C **69** (2004) 035501;

- arXiv:nucl-th/0506071.
- [52] C.J. Horowitz, Hungchong Kim, D.P. Murdock, and S. Pollock, Phys. Rev. C **48** (1993) 3078.
 - [53] G.T. Garvey, S. Krewald, E. Kolbe, and K. Langanke, Phys. Lett. **B289** (1992) 249.
 - [54] M. C. Martinez, P. Lava, N. Jachowicz, J. Ryckebusch, K. Vantournhout and J. M. Udias, arXiv:nucl-th/0505008.
 - [55] P. Lava, N. Jachowicz, M. C. Martinez and J. Ryckebusch, arXiv:nucl-th/0509103.
 - [56] A. Meucci, C. Giusti, and F.D. Pacati, Nucl. Phys. **A739** (2004) 277.
 - [57] A. Meucci, F. Capuzzi, C. Giusti, and F.D. Pacati, Phys. Rev. C **67** (2003) 054601.
 - [58] A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C **64** (2001) 014604.
 - [59] A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C **64** (2001) 064615.
 - [60] A. Meucci, Phys. Rev. C **65** (2002) 044601.
 - [61] M. Radici, A. Meucci, and W.H. Dickhoff, Eur. Phys. J. A **17** (2003) 65.
 - [62] A. Meucci, C. Giusti, and F.D. Pacati, Nucl. Phys. **A744** (2004) 307.
 - [63] H. Budd, A. Bodek, and J. Arrington, arXiv:hep-ex/0308005.
 - [64] M.J. Musolf and T.W. Donnelly, Nucl. Phys. **A546** (1992) 509.
 - [65] V. Bernard, L. Elouadrhiri, and Ulf-G. Meissner, J. Phys. G **28** (2002) R1.
 - [66] W. Pöschl, D. Vretenar, and P. Ring, Comput. Phys. Commun. **103** (1997) 217.
 - [67] G.A. Lalazissis, J. König, and P. Ring, Phys. Rev. C **55** (1997) 540.
 - [68] A. Meucci, C. Giusti, and F.D. Pacati, Nucl. Phys. **A756** (2005) 359.
 - [69] E.D. Cooper, S. Hama, B.C. Clark, and R.L. Mercer, Phys. Rev. C **47** (1993) 297.
 - [70] B.C. Clark, in *Proceedings of the Workshop on Relativistic Dynamics and Quark-Nuclear Physics*, edited by M.B. Johnson and A. Picklesimer (John Wiley & Sons, New York, 1986), p. 302.
 - [71] M. Hedayati-Poor, J.I. Johansson, and H.S. Sherif, Nucl. Phys. **A593** (1995) 377.
 - [72] J. Nieves, J.E. Amaro, and M. Valverde, Phys. Rev. C **70** (2004) 055503.